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Evaluation of an integrated pest management program for central Washington pear orchards

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ABSTRACT

Pear psylla and honeydew marking to fruit cause significant economic damage to pears in Washington, a key pear growing region of the United States. The goal of this project is to compare an integrated pest management (IPM) program using materials which selectively target pests and relies on large natural enemy populations to grower standard conventional and organic pear pest management. In six locations throughout the growing region three management techniques organic, conventional and IPM were designated to 2 ha plots in grower managed orchards. Natural enemy and pest populations were monitored using beat tray, leaf brush and trapping methods. Pest excreted honeydew levels on leaves as well as fruit marking were measured to compare the relative success of pest management programs. IPM programs, using materials which selectively target pests, successfully increased natural enemy populations and kept psylla and honeydew levels low at the end of the season. However, early season pest populations resulted in fruit marking in some years. Fruit quality in IPM programs was similar to organic orchards in 2018, and organic and conventional in 2019, but fruit quality varied by orchard. In order to maintain consistent season-long control, further revision of IPM programs for Pacific Northwest pears is necessary including management tools such as targeted insecticide applications, honeydew washing systems using designated overhead sprinklers, and natural enemy thresholds.

1. Introduction

Washington State is ranked first in pear production in the United States, growing nearly one half of the nation's fresh pears. With a crop value of $210.6 million in 2018 pears are Washington's tenth most valuable crop and an important economic driver (NASS, 2018). However, high pest pressure from pear psylla, *Cacopsylla pyricola* (Förster), two-spotted spider mites, *Tetranychus urticae* (Koch), and Mcdaniel mite, *Tetranychus mcdanieli* (McGregor) cause important economic damage. For example, pear psylla and mealybug honeydew marking resulted in 527 metric tons of d'Anjou and Bartlett culls in 2017 from just three Washington packinghouses (Strohm, 2018b). While growers are spending more than $2470 per hectare on insecticide applications, control is failing in part due to increasing resistance to insecticides as well as pear horticultural practices including large canopies and non-dwarfing rootstocks (Strohm, 2018a). Many current chemistries are no longer effective for psylla. For example, Abamectin (Agri-Mek) can have only 40% mortality, imidacloprid (Admire Pro) 30–40% mortality, permethrin (Pounce) 50% mortality, and lambda-cyhalothrin (Warrior) 10–50% mortality (Unruh, 2016), and mites have significant resistance to various miticides (Beers, 2015).

Integrated pest management (IPM) programs in pears have successfully increased natural enemy populations in the past, but pest control has been variable, often only achieved after multiple years using the program. For example, Alway (2001) found that orchards with selective IPM spray programs achieved low psylla fruit marking equal to conventional blocks and saved $370–864 per hectare in pest control costs. However, these results usually occurred after a second year in the program, suggesting the benefits of IPM tactics in pears (i.e. biological control) are not immediate. Burts (1983) observed that IPM programs increased numbers of key natural enemies of pear psylla, *Trechnites insidiosus* (Crawford), *Deraeocoris brevis* (Knight) and *Campylomma verbasci* (Meyer). Fruit marking was above levels economically acceptable to growers the first year of the program and similar to standard management (Fenvalerate, Oxythioquinox, Azinphosmethyl) in the second year of the program. Westigard et al. (1986) found increases in predator densities in four IPM orchards in Oregon, two of which achieved commercially acceptable control.

While IPM programs in the past have had variable success, organic pest management in Washington pears has generally maintained low

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pest populations and reduced fruit marking. In Washington organic orchards with natural enemy populations of *D. brevis, C. verbasci, T. insidiosus, Chrysoperla plorabunda* (Fitch)*, and Chrysopa nigricornis* (Burmeister) psylla numbers are sometimes high early in the season but generally drop to low levels during critical late season stages, resulting in less fruit marking. Growers request a program similar to organic which conserves natural enemies and provide low pest pressure and fruit marking but still allows access to a wider range of tools (DuPont, 2016).

Integrated pest management (IPM) while it does not have a legislated definition it is often described as a pest management program which incorporates multiple techniques including cultural, biological, physical and chemical controls to limit risks to human and ecosystem health (FAO, 2020; USDA, 2018). Historically these programs have focused on the use of economic thresholds for pesticide applications (UCANR, 2020). While each IPM program is different they generally include: pest identification; monitoring and assessing pest numbers and damage; guidelines for when management action is needed; preventing pest problems; using a combination of biological, cultural and physical/mechanical and chemical management tools; and after action is taken, assessing the effect of pest management (UCANR, 2020). This paper describes the test of a specifically defined integrated pest management program for pears designed to use selective insecticides and rely on conservation biological control from natural enemy populations while still allowing growers to use tools prohibited by organic management including herbicides and insect growth regulators (DuPont and Strohm, 2020).

Our recent work has demonstrated that IPM programs can enhance natural enemy populations. Orchards using IPM programs had natural enemy populations significantly greater than conventional management with numbers similar to organic (DuPont and Strohm, 2020). Natural enemy communities were largely composed of *D. brevis, C. verbasci, T. insidiosus, C. plorabunda, and C. nigricornis* (DuPont and Strohm, 2020). Differences in the total natural enemy community were driven largely by significantly larger numbers of *D. brevis* and *T. insidiosus* in early and mid-summer. The replacement of broad-spectrum insecticides pre-bloom with spray products with fewer indirect effects (insect growth regulators, sulfur, plant extract oils) in IPM and organic plots may have allowed better survivorship of overwintering insects and thus greater abundance of subsequent summer generations. Replacement of summer applications of broad spectrum products thiamethoxam, spinetoram, novaluron and spirotetramat (Actara, Delegate, Rimon and Ultor) with more selective products (neem-, petroleum-, and plant extract-based oils) maintained higher natural enemy populations. While IPM has been demonstrated to support large natural enemy populations comparable to organic, these programs will only be successful if resulting natural enemy populations result in low pest pressure and high fruit quality not yet assessed.

To date pear IPM programs have had variable success with significant fruit quality reductions in early years before natural enemy populations are established. Roadblocks to adoption include consistent pest suppression and the need for specific management guidelines which would target pests at key life stages with efficacious products and incorporate cultural controls. IPM could provide a sustainable alternative to growers if detailed management guidelines result in dependable pest suppression and fruit quality. In this paper we assess the ability of IPM programs to achieve high natural enemy populations, low pest populations and high fruit quality across three years in twenty-eight locations. Current evaluation of IPM programs for pear in Washington is critical to increase grower confidence and adoption for one of the largest pear growing regions in the world.

2. Materials and methods

2.1. Field sites and experimental treatments

Study sites were located in the Wenatchee River Valley, Washington USA in orchards planted primarily with d'Anjou and Bartlett varieties. This river valley region between the towns of Wenatchee and Leavenworth grows approximately 4000 ha of tree fruit, of which 3600 ha are pears, making it the second largest pear growing region in the United States (Cropscape, 2020). Six locations were designated throughout the production zone where each location had similar growing conditions and elevations. Each treatment was applied to 2 ha study plots in each location where plots within a location were within close proximity (within 2 km). Locations were consistent for all three years, however plots within each location varied in some cases between years 2017 and 2018.

Treatments consisted of three management systems: organic, conventional and IPM. Each treatment followed specific rules, but spray timings and materials were not rigidly aligned among orchards. Organic management followed the USDA certified organic standards (Organic Food Production Act §205) which prohibits the use of synthetic products (Tables A.1-3). Conventional management was grower standard practice, which often involved the use of multiple broad-spectrum materials such as organophosphates, pyrethroids, neonicotinoids, spinosyns, and abamectin based on consultant recommendations using a combination of calendar and pest pressure prescriptions see tables Tables Appendix 1-3. In 2017, growers using IPM management were asked to avoid a list of broad spectrum insecticides. In 2018 and 2019, IPM growers used a specific toolbox of cultural controls and pesticides which were designed to contain selective products with less documented negative impact on natural enemies (Table 1, Tables Appendix 1-3; DuPont & Strohm 2020).

Table 1
Integrated Pest Management Toolbox. Growers using this system of management selected tools from within this toolbox.

Cultural Controls		
Season Long	Good coverage	
	Moderate fertility	
	Remove water sprouts	
	Mating disruption for codling moth	
	Weed management timing (with respect to mites)	
Preferred Chemical Controls[a]		
Pre-bloom	petroleum oil	lime sulfur
	sulfur	buprofezin
	kaolin	pyriproxyfen
	diflubenzuron	*Isaria fumosorosea* apopka strain 97
Petal fall	petroleum oil	azadirachtin
	pyriproxyfen	buprofezin
	rosemary oil	fenbutatin oxide
	Isaria fumosorosea apopka strain 97	
Cover sprays	rosemary oil	spinosad
	diflubenzuron	azadirachtin
	Bacillus thuringiensis subsp. kurstaki	codling moth granulosis virus
	chlorantraniliprole	methoxyfenozide
	petroleum oil	cyantraniliprole
		cinammon oil
Summer Miticides	spirodiclofen	bifenazate
	fenbutatin oxide	clofentezine
	petroleum oil	hexythiazox

[a] Growers were asked to avoid products with high negative impact on natural enemies or low efficacy including: lambda-cyhalothrin, novaluron, chlorpyrifos, thiamethoxam, malathion, esfenvalerate, acetamiprid, abamectin, pyridaben, imidacloprid, spirotetramat.

2.2. Pest and natural enemy monitoring methods

Plots were scouted once per week from early April to mid-September in 2017, and early April to early October in 2018 and 2019 using beat trays, leaf samples, earwig traps, and sticky traps with volatile lures. Beginning dates usually occurred within a week of the season's first insecticide applications, and end dates were around two weeks following d' Anjou harvest, usually a month after the final insecticide application of the season.

2.3. Beat trays

Within each plot, thirty samples of canopy dwelling arthropods were collected using the beat tray method. Each beat tray sample (one 'tray') involves holding a 45 × 45 cm white sheet 30 to 45 cm underneath a horizontal branch and striking it three times with a stiff rubber stick to dislodge insects onto the tray, which are then counted. Branches selected for sampling were 1–2 m above ground and 1.5 to 4 cm in diameter. The number of pear psylla adults and natural enemies per beat tray were counted. Major natural enemies whose counts were included in analysis include adult *T. insidiosus*, Aranae (spiders), Anthocoridae (minute pirate bugs), *C. verbasci* (common mullein bugs), Chrysopidae (green lacewings), Coccinellidae (ladybird beetles), *D. brevis, Forficula auricularia* (European earwig), Geocoridae (big-eyed bugs), Hemerobiidae (brown lacewings), and Nabidae (damsel bugs).

2.4. Traps

Predator and parasitoid densities were also measured using sticky card traps baited with attractive lures containing plant volatiles. Baited traps were used to increase capture of key natural enemies per (Jones et al., 2011). Each trap lure combination was placed in each of four replicated transects in each orchard plot at a distance of at least 30 m apart and 1 to 2 m above the ground. Each tree with a sticky card trap also contained one earwig trap. All lures were replaced at six-week intervals. All traps were checked once per week and the number of insects was counted.

Traps were baited with one of three lure combinations. A yellow sticky card (23 × 14 cm) with AMP lure (acetic acid 3 ml per lure + methyl salicylate 3.3 ml per lure + 2-phenylethanol 1 ml per lure) was used to collect adult green lacewings (*C. plorabunda*). A white sticky card (18 × 18 cm) combined with a squalene lure (0.5 ml squalene per lure) was used to collect adult green lacewing (*C. nigricornis*). Lures were assembled per (Jones et al., 2011). A yellow sticky card combined with a *C. verbasci* synthetic sex pheromone spiral (gel matrix releasing butyl butyrate compounds; Scentry biologicals) was used to collect male *C. verbasci* adults. Both types of yellow sticky card traps were used to collect adult *T. insidiosus* wasps. Additionally, adults of *D. brevis*, brown lacewings, and ladybeetles were collected on all of these traps. Sections (7.6 × 35.6 cm) of single side corrugated cardboard were rolled into a cylindrical shape and placed in the canopies of twelve trees within each plot to sample earwigs (Helsen et al., 1998).

2.5. Leaf samples

Leaf samples were taken to determine pest populations. One hundred leaves were collected from ten randomly selected trees distributed throughout each plot. In the early season, five fruiting bud leaves were collected from both the lower and upper canopies of each tree. Lower canopy leaves were selected with two to three leaves in the inner, middle, and outer sections of scaffold limbs 1.2 to 1.8 m from the ground. Upper canopy leaves were taken from two fruit clusters using an extendable pole pruner. During summer, leaves were selected from both fruit clusters and shoots.

Collected leaves were kept cool and returned to the lab to be sampled using a leaf brusher (Leedom Enterprises). Leaves were run through two motorized brushes which dislodge arthropods onto a revolving glass plate, creating a composite sample of arthropods to be counted under a stereoscopic microscope (Burts, 1988; Horton, 1999a). Arthropods collected from the leaves included pear psylla eggs, young psylla nymphs (instars 1–3), old psylla nymphs (instars 4–5), mummified psylla nymphs, mealybugs, European red mites, Panonychus ulmi; spider mites *T. urticae*, *T. mcdanieli*; and pear rust mites, Epitrimerus pyri (Nalepa).

2.6. Honeydew

Pear psylla are an indirect pest where marking from honeydew excreted by the insect versus direct feeding cause damage to the fruit. Growers use honeydew levels to predict subsequent fruit marking which are assumed to be correlated. Pear psylla honeydew residues on leaves were measured to assess infestation and injury levels. Leaves were collected from ten randomly selected trees distributed throughout each site. Five spur or shoot leaves were collected from both the lower and upper canopies of each tree for a total of 100 leaves per plot. Lower canopy leaves were selected from the middle to inner sections of scaffold limbs four to six feet from the ground. Upper canopy leaves were taken from two shoots using an extendable pole pruner. Upper and lower canopy leaves were mixed into a single bag for each plot. Leaf samples were collected at two time points, approximately the week of Bartlett pear harvest (August 20 to September 8) and d'Anjou pear harvest (September 5 to 27). A sub-sample of 50 leaves were removed from each bag and placed inside a small plastic container. Deionized water (50 ml) was added and each container was shaken for 60 s to wash honeydew from leaves. The wash from each container was poured through fine mesh to remove large particles and into a 200 ml glass beaker. Three small amounts of wash were pipetted out to measure the Brix value using a RX-5000α-Bev digital refractometer (Atago Co. Ltd.). The mean Brix value was reported for each wash sample.

2.7. Fruit grading

One week prior to harvest, ten d'Anjou pear fruits were inspected on twenty randomly selected trees at each site. Care was taken to look at fruits both near the canopy center and on the periphery. Fruits were categorized as either U.S. #1 (best), Washington Fancy (decent), or Cull (unmarketable) based on USDA pear packing grades for pear psylla marking (USDA, 2007). In short, US #1 had heavy surface marking < 1.25 cm^{-1}, moderate marking < 1.9 cm^{-1}, or thin marking < 25%. WA Fancy had heavy surface marking < 1.9 cm^{-1}, moderate < 3.2 cm^{-1}, or thin marking < 50% of surface area. Culls (third grade) had more than 5% heavy marking, 10% moderate and 75% thin. Only d'Anjou were analyzed because fruit marking from psylla and mealy bug are generally low in Bartlett due to earlier harvest timing and lower attractiveness to insect pest of Bartlett.

2.8. Natural enemy impact scores

The potential impacts of products on natural enemies was calculated for each spray used during the season in each plot. Individual product ratings for western predatory mites, mite predators, coccinellids, lacewings and predatory true bugs were converted to numerical ratings from low (1), low to medium (2), medium (3), medium to high (4) and high (5) given in the Washington State University Crop Protection Guide (DuPont et al., 2020). These ratings are based on literature review of multiple sources. An individual product's score is the average of the rating for each of the five natural enemy types. A plot's score is the sum of the score for each spray used during the season, where higher scores equal higher natural enemy impact (DuPont and Strohm, 2020).

Table 2
Effect of management program on natural enemy abundance per beat tray sample in 2017, 2018, and 2019.[a]

	Conventional	IPM	Organic	treatment	week[b]	treatment × week[b]
	Mean (+/−SE)	Mean (+/−SE)	Mean (+/−SE)	*P*	*P*	*P*
2017	0.04 ± 0.2	0.67 ± 0.23	0.52 ± 0.2	0.110	**0.049**[c]	0.993
2018	0.07 ± 0.09	0.56 ± 0.09	0.5 ± 0.1	**0.005**	0.109	0.182
2019	0.05 ± 0.06	0.59 ± 0.08	0.55 ± 0.07	**0.001**	**< 0.001**	0.110

[a] Average per beat tray per week
[b] Bloom week, weeks before or after bloom
[c] Significance noted in boldface.

2.9. Statistical analysis

Insect data were analyzed using the mixed procedure analysis of variance (ANOVA) (SAS 9.4, SAS Institute Inc. 2016). A repeated measures ANOVA of average insect abundance per week was performed with week (defined as weeks before and after bloom) as a repeated measure and location (block) as a random effect. Two to four plots of different treatments in close geographic proximity (less than one mile) were considered to be within one location. Due to significant by year interactions data analysis was conducted for each year individually. When interactions between treatment and week were found, analysis was performed on partitioned time periods of the data (pre-bloom- bloom-week −5 to −2; bloom- bloom-week −1 to 1; early season- bloom week 2 to 7; mid-season- bloom-week 8 to 16; late season- bloom-week 16 to 24). Treatment differences were discerned using Tukey's honest significant difference test ($\alpha = 0.05$).

A stepwise regression (SAS 9.4) was used to select the best grouping of fruit quality predictor variables to account for the most variance in fruit quality for programs that rely on natural enemies (organic and IPM) using 2019 data. Stepwise regression is a semi-automated process of building a model by successively adding or removing variables based on the *t*-statistics of their estimated coefficients. At each step, for each variable currently *in* the model, the *t*-statistic is calculated for the estimated coefficient, it is squared and this is reported as the "*F*-to-remove" statistic. For each variable *not* in the model, the *t*-statistic is computed for what the coefficient *would* have if it were the next variable added, the result is squared, and it is reported as the "*F*-to-enter" statistic. At the next step, the program automatically enters the variable with the highest *F*-to-enter statistic, or removes the variable with the lowest *F*-to-remove statistic, in accordance specified parameters. Parameters used were *F*-statistic selection entry 0.1 and *F*-statistic removal 0.15. Percentage of US#1 fruit was the dependent variable and tree size, honeydew washing (number of washes per season based on grower records), natural enemy impact score, percent pear cover within 1 km, and average number of natural enemies per beat tray (pre-bloom, bloom, early summer, late summer and harvest) were the independent variables. Percent area covered by pear orchards in a 1 km^{-1} area around the monitored pear orchard (percent pear cover) was measured using CropScape – Cropland Data layer (USDA https://nassgeodata.gmu.edu/CropScape/). The rationale is that a more homogeneous pear landscape may experience higher pest pressure. Tree size was categorized as large or small where pear trees on standard rootstocks were considered large and trees on Old Home 87 semi-dwarfing rootstock were considered small. Number of honeydew washes per season was evaluated by grower survey.

A linear regression of the model selected by stepwise regression was conducted where percent of US #1 fruit was the dependent variable and tree size (-0.04) + number of honeydew washes (-0.051) + average number of natural enemies per tray in early summer (8.6) + average number of natural enemies per tray during harvest (30.2) + the natural enemy impact score (0.34) were the independent variables. Multipliers for each independent variable were derived from parameter estimates outputs from the backwards stepwise regression.

To discern similarity and differences between natural enemy assemblages based on species, we used a nonmetric multidimensional scaling (NMS) ordination, with Sorenson distance measure (PC-ORD version 4.0 software, McCune and Mefford (1999). NMS is a distance measure which uses ranked distances to linearize the distances in species or environmental space. NMS is an effective method for multivariate data reduction and analysis of ecological community data sets (McCune and Grace 2002) particularly appropriate for extracting important gradients in community composition, which can then be related to desired environmental responses. NMS is well-suited to data that are non-normal or discontinuous. Multiple-response Permutations Procedures (MRPP) were also employed to test significance among the experimental factors within the datasets (McCune and Grace, 2002; Mielke, 1984). This procedure creates p-values to determine statistical significance between groups in a system.

3. Results

3.1. Natural enemy communities

IPM programs conserved high natural enemy populations in three consecutive years. Natural enemy abundance in beat trays was significantly greater in organic and IPM plots relative to conventional in

Table 3
Summary statistics for repeated measures analysis of psylla adult and nymph populations in 2017, 2018 and 2019.

			treatment	week[a]	TxW[b]
		Degrees of freedom	*P*	*P*	*P*
2017	Adults	df = 2, 10, df = 18, 286, df = 36, 286	0.681	**< 0.0001**[c]	0.977
	Nymphs	df = 2, 10, df = 18, 286, df = 36, 286	0.518	**< 0.0001**	0.963
2018	Adults	df = 2, 10, df = 20, 341, df = 40, 341	0.204	**< 0.0001**	0.999
	Nymphs	df = 2, 10, df = 20, 341, df = 40, 341	**0.039**	**< 0.0001**	0.406
2019	Adults	df = 2, 10, df = 21, 296, df = 42, 296	**0.005**	**< 0.0001**	**< 0.0001**
	Nymphs	df = 2, 10, df = 21, 296, df = 42, 296	**0.004**	**< 0.0001**	**< 0.0001**

[a] Bloom week, weeks before or after bloom.
[b] T × W = treatment × bloom week.
[c] Significance noted in boldface.

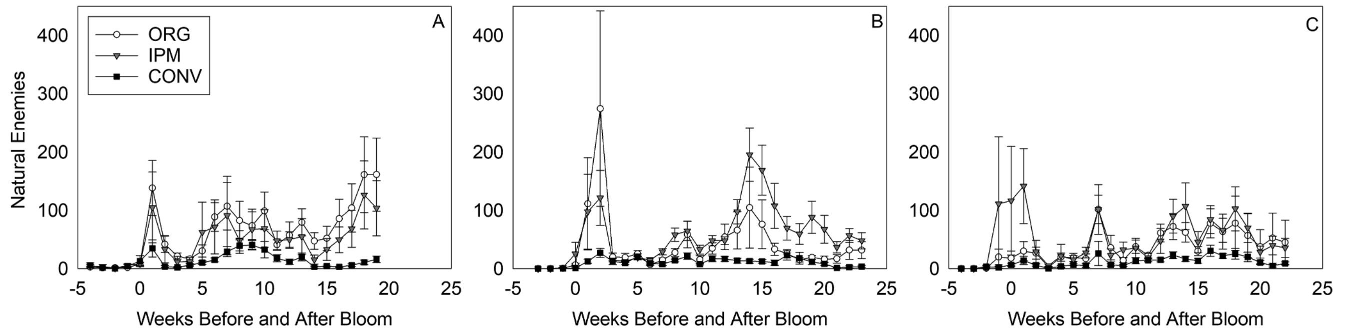

Fig. 1. Mean natural enemy abundance per beat tray (+/−SE) in pear orchards in 2017 (A), 2018 (B), and 2019 (C). Organic (white circle), IPM (gray triangle), and conventional (black square).

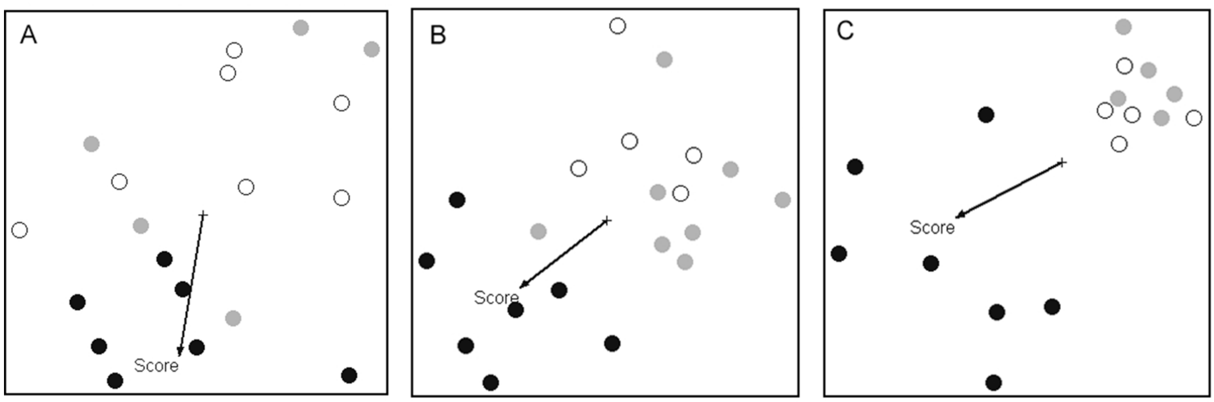

Fig. 2. Nonmetric Multidimensional Scaling Analysis of Natural Enemy Community in 2017 (A), 2018 (B), and 2019 (C). Organic (white); IPM (grey), and conventional (black). Vectors represent correlation with the main matrix of predictive variables with R^2 greater than 0.4.

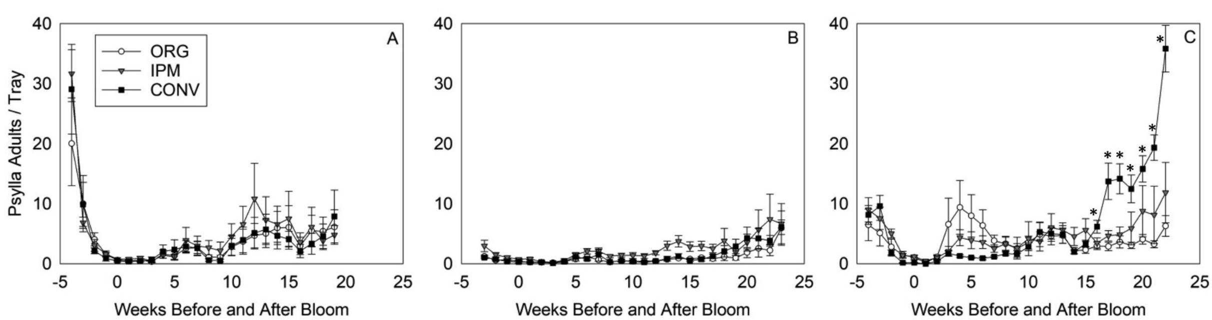

Fig. 3. Mean number of pear psylla adults collected per beat tray (+/−SE) in organic (white circle), IPM (gray triangle), and conventional (black square) orchards in 2017 (A), 2018 (B), and 2019 (C). Significant weekly treatment differences noted with asterisks.

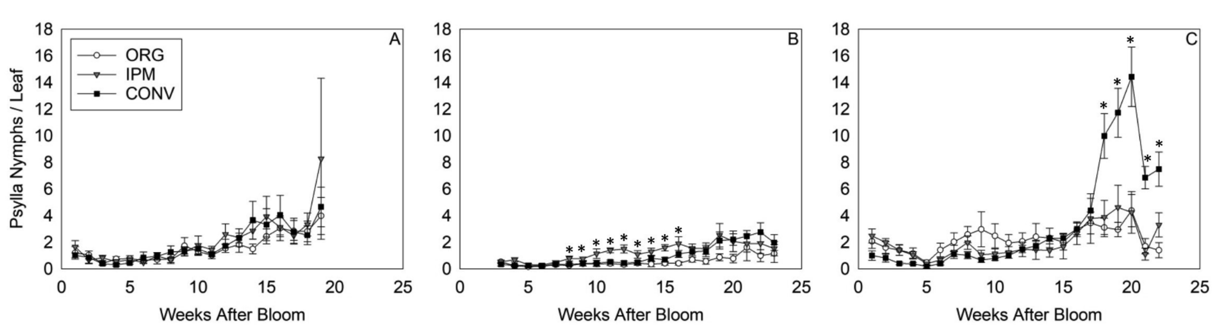

Fig. 4. Mean number of pear psylla nymphs per leaf (+/−SE) in organic (white circle), IPM (gray triangle), and conventional (black square) orchards in 2017 (A), 2018 (B), and 2019 (C). Significant weekly treatment differences noted with asterisks.

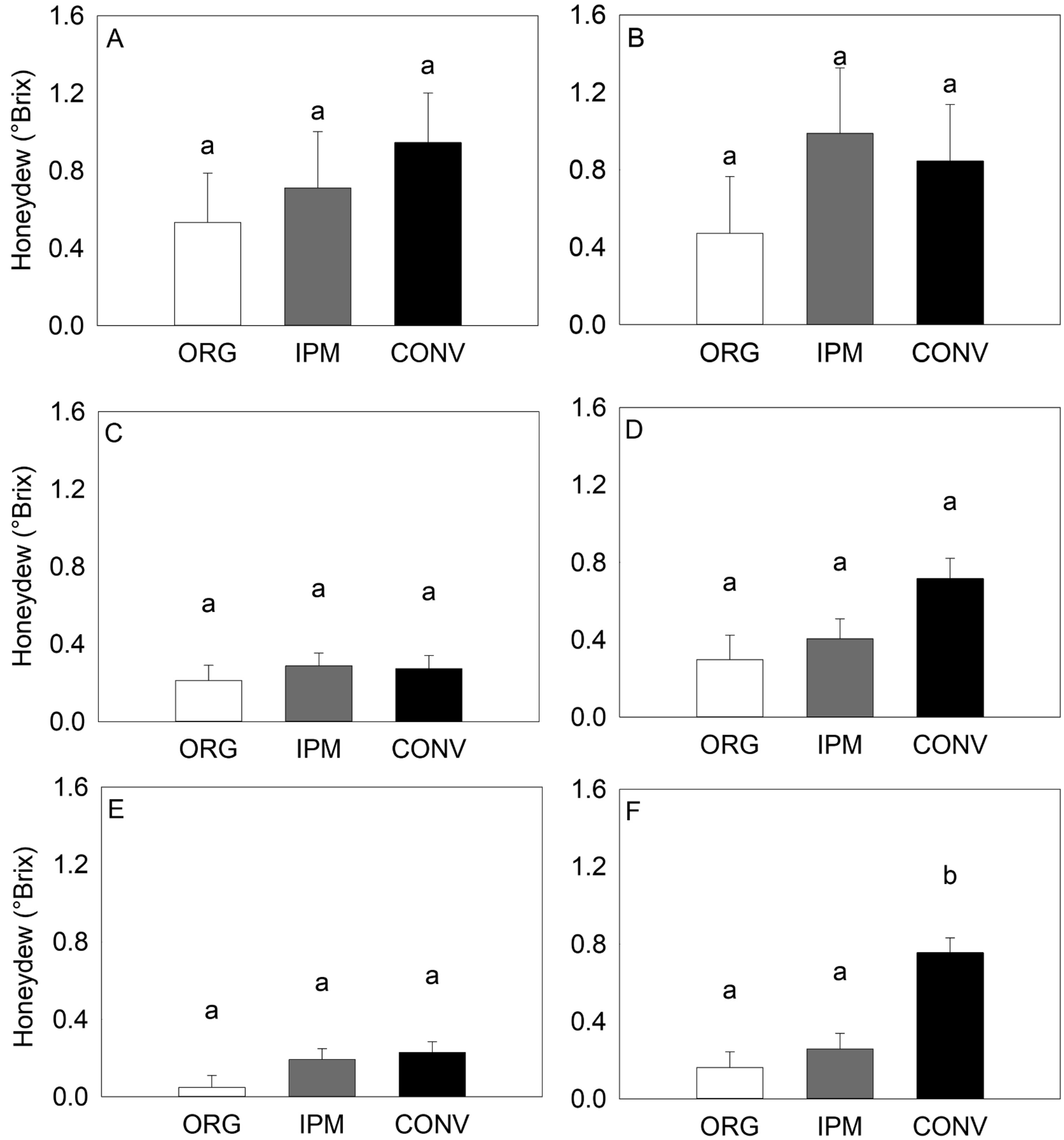

Fig. 5. Mean honeydew brix (+/−SE) recorded from washed leaves during 2017 Bartlett harvest (A), 2017 d'Anjou harvest (B), 2018 Bartlett harvest (C), 2018 d'Anjou harvest (D), 2019 Bartlett harvest (E), 2019 d'Anjou harvest (F). Organic (white), IPM (gray), and conventional (black).

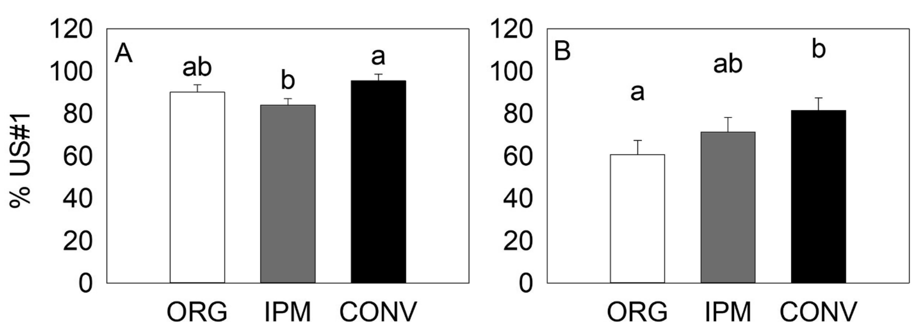

Fig. 6. Mean percent US#1 grade (+/−SE) d'Anjou pear fruits inspected for honeydew marking prior to harvest in 2018 (A) and 2019 (B). Organic (white), IPM (gray), and conventional (black).

2018 and 2019 starting at bloom week one (bloom weeks are week before and after bloom) (Table 2, Fig. 1) with a trend toward higher populations in IPM plots beginning mid-season in 2017. Beat tray abundance of natural enemies in organic and IPM plots was often ten times that measured in conventional plots. For example, the maximum mean per tray for natural enemies in organic, IPM, and conventional plots respectively was 1.4, 2, and 0.1 (2017); 0.9, 1.5, and 0.1 (2018); and 1.3, 0.9, and 0.2 (2019).

Multivariate analysis also showed natural enemy communities in IPM were different from conventional with IPM communities becoming more similar to organic by 2019. An analysis of natural enemy communities collected in beat trays was conducted using Non-metric

Table 4
Summary statistics for the stepwise regression of predictor variables on fruit quality (% US#1 fruit) in IPM and organic orchard blocks.[a]

	Parameter Estimate	Chi-Square
tree size	−0.04 ± 0.02	3.67
honeydew washing	−0.51 ± 0.32	2.51
natural enemies early summer	8.57 ± 4.56	3.53
natural enemies harvest	30.20 ± 14.75	4.19
natural enemy impact score	0.34 ± 0.17	3.96

[a] Variables were added progressively to the regression until no further improvement was reached with α = 0.1 to enter and α = 0.15 to remove.

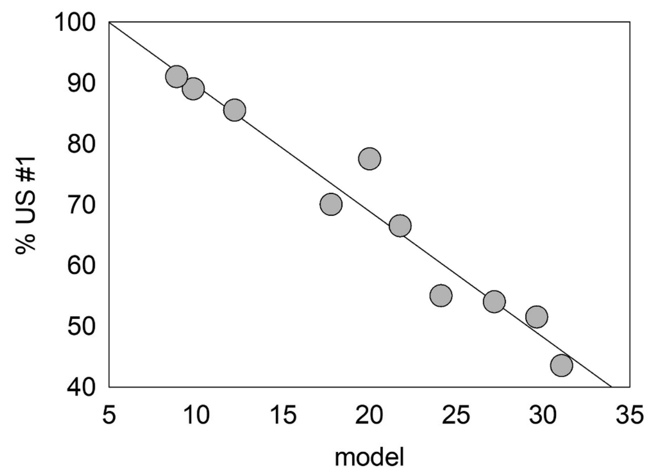

Fig. 7. Regression analysis where percent of US number one fruit is the dependent variable and tree size (-0.04) + number of honeydew washes (-0.051) + average number of natural enemies per tray in early summer (8.6) + average number of natural enemies per tray during harvest (30.2) + the natural enemy impact score (0.34) is the independent variable. The model was significant (p < 0.0001; R2 = 0.95).

multidimensional scaling (NMS) with a user supplied seed of 5002 (2017, 2019) and 2003 (2018) (Fig. 2). For 2017 NMS analysis found a successful two-dimensional solution with final stress of 9.9 and instability of 0.0000. MRPP analysis showed that natural enemy communities in organic were significantly different than conventional ($P = 0.007$). For 2018 a successful two-dimensional analysis had a final stress of 11.85 and instability of 0.000. MRPP analysis showed that natural enemy communities in organic and IPM systems were significantly different than that of conventional ($P < 0.001$). In 2019 the successful two-dimensional analysis had a final stress of 9.76 and instability of 0.000. MRPP analysis showed that natural enemy communities in organic and IPM systems were significantly different than that of conventional ($P < 0.001$).

Program selectivity drove distribution of the NE community (Fig. 2). Vectors represent correlation with the main matrix of predictive variables with R^2 greater than 0.4. The greater the length of the vector the higher the R^2. Score, representing the number or non-selective insecticides used, was highly correlated with conventional plot natural enemy insect communities in all years (Fig. 2). Conventional management had a higher score where more non-selective chemistries were used. This correlated with natural enemy communities in conventional plots which had many fewer natural enemies, often ten times less than in organic and IPM treatments.

Natural enemy communities in IPM became more similar to organic after two years using selective chemistries. In 2017 IPM communities were not significantly different than conventional or organic with significant differences only between conventional and organic ($P = 0.007$). In 2018 and 2019 IPM communities grouped with organic and were significantly different than conventional ($P < 0.001$). While in 2018 natural enemy communities were distinct, when all plots had been more than two years in IPM management in 2019 natural enemy communities in IPM and organic were very well grouped together and highly separated from communities under conventional management.

3.2. Pest populations

IPM programs successfully kept pest populations low at the end of the season but resulted in some detrimental early-mid season populations. In 2017 neither psylla adult nor psylla nymph populations were significantly different in IPM compared to conventional management (Fig. 3A, 4A, Table 3). In 2018 psylla adult populations were not significantly different in IPM than conventional when analyzed across the season but psylla nymph numbers varied by date (Fig. 3B, Fig. 4B, Table 3). Analysis of bloom weeks eight to sixteen showed a significant affect for treatment ($P = 0.002$) with no treatment by date interaction. Psylla nymph numbers in IPM averaging 1.3 were significantly higher than conventional 0.6 ($P = 0.007$) or organic 0.6 ($P = 0.004$). In 2019 psylla adult and nymph populations were significantly different with a significant treatment by date interaction (Table 3). Both psylla adult and nymph populations increased greatly in the last seven weeks of the season in conventional plots compared to organic and IPM plots (Fig. 3C, 4C) with an average of 17 psylla adults per tray in conventional compared to 4 in organic ($P = 0.004$) and 6 in IPM ($P = 0.0024$) and 9 psylla nymphs per leaf in conventional compared to 3 in organic ($P < 0.001$) and 4 in IPM ($P = 0.004$). At the week 20 peak, conventional plots had 14 nymphs per leaf while organic and IPM plots had just 4–5 nymphs per leaf.

3.3. Honeydew

In 2017, the mean Brix value for all plot types exceeded 0.4 at Bartlett and d'Anjou pear harvests with no significant effect of treatment (Fig. 5A, $P = 0.38$ Bartlett; Fig. 5B, $P = 0.40$ d'Anjou). During the 2018 and 2019 Bartlett pear harvests, the mean Brix value for all plot types was < 0.3 with no significant effect for treatment (Fig. 5C, $P = 0.65$ 2018; Fig. 5E, $P = 0.14$ 2019). In the 2018 and 2019 at d'Anjou pear harvests (approx. 2 weeks later), mean Brix values increased slightly in organic and IPM plots, but never exceeded 0.4. The mean Brix values in conventional plots increased to at least 0.7 in both years, significantly greater than IPM and organic plots in 2019 (Fig. 5F, $P < 0.001$).

3.4. Fruit grading

Fruit quality based on insect marking in IPM programs was similar to organic orchards in 2018, and organic and conventional in 2019. In 2018 on average, IPM plots had 84% US#1 fruit compared to 96% in conventional plots (Fig. 6A; $P = 0.013$). IPM had a greater number of fruit downgraded to WA Fancy: 11% IPM versus 4% conventional ($P = 0.007$). Organic plots were intermediate with 90% US#1 and 7% WA Fancy fruit. All three plot types had similar numbers of culled fruit in 2018: 2.8% (organic), 4.5% (IPM), and 1.3% (conventional) with no significant effect of treatment ($P = 0.15$). In 2019 there was a significant effect of treatment on US#1 fruit ($P = 0.023$) where organic plots had fewer US#1 fruit (61%) than conventional plots (81%) (Fig. 6B; $P = 0.019$). There was also a significant effect of treatment on culls ($P = 0.019$) with more culls in organic (25%) relative to conventional (7%) ($P = 0.016$). For IPM plots, the number of US#1 (71%) and cull fruit (16%) and Fancy (13%) was intermediate and not statistically different from organic or conventional plots (Fig. 6B).

3.4.1. Relationship between insect populations and fruit grading

From the initial predictor variables tree size, honeydew washing (number of washes per season), natural enemy impact score, percent pear cover within 1 km, and average number of natural enemies per tray (pre-bloom, bloom, early summer, late summer and harvest), only the variables honeydew washing and average number of natural enemies per tray early summer, average number of natural enemies during harvest, natural enemy impact score and tree size were significant. Percent pear cover within 1 km, average number of natural enemies pre-bloom, bloom and late summer were dropped from the regression model based on backwards stepwise linear regression (Table 4). Acceptable levels of fruit marking in IPM and organic orchards were associated with smaller sized trees, honeydew washing, natural enemies in early summer/harvest, and natural enemy impact scores. The model resulting from the stepwise regression accounted for 95% of the variation in fruit quality (Fig. 7: $P < 0.0001$; R2 = 0.95).

4. Discussion

4.1. Natural enemy communities

IPM programs successfully conserved natural enemy communities. The natural enemy population was composed primarily of *D. brevis, C. verbasci, T. insidiosus, Chrysoperla plorabunda, and Chrysopa nigricornis* (DuPont and Strohm, 2020). These natural enemy communities in IPM plots became more like those in organic plots over time (Fig. 2). Plots having spray programs with higher natural enemy impact scores (i.e. more broad-spectrum sprays) had smaller, less complex natural enemy communities (Fig. 2). Therefore the ability of IPM programs to conserve natural enemies was highly related to pesticide program selectivity.

4.2. Pest populations

IPM programs kept psylla populations and honeydew low at the end of the season in all years, a difficult period for insect management, however early season pest populations were a challenge in 2019. During the final weeks of the growing season it is often difficult to maintain insect control in pear orchards. Large, dense pear canopies often make late season spray coverage difficult. With increasing resistance to available insecticides, honeydew-related fruit marking can result in large numbers of downgraded fruit (Beers, 2015; Strohm, 2018b; Unruh et al., 2015). In this study we saw a similar trend in conventional plots where psylla nymphs reached an average of 14 per leaf in bloom week 20 in 2019 resulting honeydew levels spiked at the end of the season (Fig. 5F). In contrast IPM plots had late season nymph numbers of 4–5 per leaf similar to organic plots. In IPM honeydew levels stayed low through Anjou harvest. However, in 2019 IPM and organic plots had an early season peak of psylla which likely caused fruit marking. In 2019 three weeks after bloom IPM and organic plots had an average of 1.4 psylla nymphs per leaf compared to only 0.4 in conventional plots. Other studies have also shown that early season natural enemy numbers can be critical for effective biological control of psylla and mealy bug. Gut et al. (1982) found that where natural enemy communities were large and more complex with peak populations in May and early June the psylla populations were kept below economically damaging thresholds.

4.3. Fruit grading

While average IPM fruit quality was not significantly different than organic in 2018 and 2019 and not significantly different than conventional in 2019, overall success of these programs measured as boxes of high-grade fruit varied from orchard to orchard. In 2018 all programs had relatively high fruit quality with % US#1 ranging between 84 and 96% (IPM 84%; conventional 96%; organic 90%). 2019 was a higher psylla pressure year and resulted in a much wider range of fruit quality with conventional averaging 81% compared to 61% in organic and 71% in IPM. In 2019 the packout of US#1 fruits varied greatly between IPM plots with three over 75% packout (78%, 86% and 89%) two plots with low packouts (67% and 44%). A multiple regression analysis was done to analyze which factors might contribute to the success of organic and IPM programs (both of which rely on natural enemies) for 2018 and 2019. The 2019 analysis found that natural enemies in early summer and at harvest as well as tree size, number of honeydew washes, and the score of the spray program were important predictors of fruit quality (Fig. 7). Interestingly the amount of pear cover in the surrounding area was not significant in this analysis. Of the three sites with percentage of harvested fruit packed at over 80%, one had small trees and two had honeydew washing systems.

4.4. Conclusions

IPM programs successfully increased natural enemy populations and kept psylla and honeydew levels low at the end of the season. However, for season-long successful pest management, further revision of these programs is critical. Unlike other orchard pests like codling moth, psylla management is not currently tied to a phenology model. Application of selective products such as insect growth regulators require optimized timing to be most effective (Higbee et al., 1995; Horton, 1999b; Krysan, 1990). Honeydew washing consists of a separate-targeted overhead irrigation system designed to apply several hours of washing at key times during the growing season specifically to remove psylla and mealybug honeydew (Brunner and Burts, 1981). Addition of these systems to pear blocks gives growers an additional tool to control fruit marking and may allow more flexibility to adhere to IPM programs that have selective tools especially early in the season before natural enemy populations have reached sufficient levels to control pests. Additionally, establishment of natural enemy:pest action thresholds would allow growers to reduce late season insecticide applications when there are sufficient natural enemies to maintain low pest populations. These ratios would take into account not only the predation/parasitism efficiency of natural enemies (Heinz et al., 1993) but also the pest and natural enemy growth capacity (Gontijo and Carvalho, 2020; Puebla et al., 2018). In order to maintain consistent season-long control, further revision of IPM programs for Pacific Northwest pears is necessary including key management tools such as targeted insecticide applications, honeydew washing systems using designated overhead sprinklers, and natural enemy thresholds.

CRediT authorship contribution statement

S. Tianna DuPont: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing - original draft. **Christopher Strohm:** Investigation, Writing - original draft. **Louis Nottingham:** Methodology, Writing - review & editing. **Dalila Rendon:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table Appendix 1
Pesticide Program and Natural Enemy Impact Scores 2017.[1]

Site	System	Pre-Bloom Sprays[2]	Post-Bloom Sprays[2,3]	Score
11	IPM	kaolin/chlorpyrifos/malathion + novaluron/ lambda-cyhalothrin/abamectin + novaluron/ thiamethoxam/abamectin	novaluron/ spirotetramat + spinetoram + thiamethoxam/ fenpyroximate + spinetoram/ cyflumetofen + imidacloprid	76
12	IPM	kaolin + pyriproxyfen/cyantraniliprole/ sulfur + pyriproxyfen/cyantraniliprole	calcium carbonate/cyantraniliprole/fenbutatin oxide + calcium carbonate/cyantraniliprole + azadirachtin	34.8
20	IPM	novaluron/abamectin	buprofezin/abamectin + buprofezin/spirotetramat/ codling moth granulosis virus + spinetoram/spirotetramat/ spirodiclofen + azadirachtin + thiamethoxam/ fenpyroximate + acetamiprid/imidacloprid/ bifenazate + spinetoram/acetamiprid/cyflumetofen	61.9
21	IPM	kaolin/chlorpyrifos/malathion + calcium carbonate/novaluron	calcium carbonate/novaluron/abamectin/ spirotetramat + calcium carbonate/novaluron/spirodiclofen/spirotetramat/ clofentezine + azadirachtin/rosemary oil + spinetoram/thiamethoxam/hexythiazox/ azadirachtin + azadirachtin	62.5
24	IPM	kaolin/chlorpyrifos + novaluron/abamectin	calcium carbonate/novaluron/abamectin/ spirotetramat + calcium carbonate/buprofezin/spirotetramat + spinetoram/ hexythiazox + acequinocyl + acetamiprid/ cyflumetofen	52.7
27	IPM	kaolin/sulfur + kaolin/sulfur	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus + azadirachtin	31.4
7	CONV	kaolin + kaolin/sulfur/malathion/ chlorpyrifos + novaluron/lambda-cyhalothrin	novaluron/thiamethoxam/abamectin + novaluron/ spirotetramat + spinetoram + thiamethoxam/ fenpyroximate + imidacloprid/spirotetramat/ spirodiclofen + spinetoram/azadirachtin/cyflumetofen	85.4
14	CONV	kaolin + kaolin/chlorpyrifos/malathion/ sulfur + novaluron/lambda-cyhalothrin	novaluron/thiamethoxam/abamectin + novaluron/ spirotetramat + spinetoram + thiamethoxam/ fenpyroximate + imidacloprid/spirotetramat/ spirodiclofen + spinetoram/cyflumetofen/azadirachtin	85.4
17	CONV	kaolin/sulfur/chlorpyrifos/lambda-cyhalothrin + abamectin/lambda-cyhalothrin/novaluron	novaluron/spirotetramat/abamectin + spirotetramat/ novaluron + spinetoram/etoxazole + thiamethoxam/ fenpyroximate + spinetoram/imidacloprid/ spirodiclofen + spinetoram/imidacloprid/ cyflumetofen	90.9
18	CONV	novaluron/abamectin	novaluron/abamectin + novaluron/spirotetramat/ etoxazole/codling moth granulosis virus + spinetoram/spirotetramat/ spirodiclofen + azadirachtin + thiamethoxam/ fenpyroximate + acetamiprid/ imidacloprid + bifenazate + spinetoram/acetamiprid/ cyflumetofen	69.9
23	CONV	kaolin + kaolin/chlorpyrifos/ malathion + calcium carbonate/novaluron	calcium carbonate/novaluron/abamectin/ spirotetramat + calcium carbonate/novaluron/spirodiclofen/spirotetramat/ clofentezine + azadirachtin/rosemary oil + spinetoram/thiamethoxam/hexythiazox/ azadirachtin + azadirachtin/rosemary oil + imidacloprid/fenbutatin oxide/azadirachtin/ rosemary oil + spinetoram/acetamiprid/cyflumetofen	85.2
26	CONV	kaolin + kaolin/chlorpyrifos + novaluron/ abamectin	calcium carbonate/novaluron/abamectin/ spirotetramat + calcium	58.8

(*continued on next page*)

Table Appendix 1 (*continued*)

Site	System	Pre-Bloom Sprays[2]	Post-Bloom Sprays[2,3]	Score
			carbonate/buprofezin/spirotetramat + spinetoram/ hexythiazox + thiamethoxam/acequinocyl/ azadirachtin + acetamiprid/cyflumetofen	
8	ORG	kaolin/sulfur + kaolin/sulfur/azadirachtin	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus + azadirachtin	33.4
10	ORG	kaolin/sulfur x2[4] + kaolin/calcium carbonate + calcium carbonate/azadirachtin	spinosad/azadirachtin/codling moth granulosis virus x3 + azadirachtin/codling moth granulosis virus x4 + lime sulfur	62.5
13	ORG	kaolin + kaolin/sulfur + kaolin	azadirachtin/calcium carbonate + azadirachtin/rosemary oil + spinosad/azadirachtin/codling moth granulosis virus/rosemary oil + azadirachtin/codling moth granulosis virus/rosemary oil + azadirachtin/codling moth granulosis virus + diatomaceous earth + azadirachtin/pyrethrin	44.1
16	ORG	lime sulfur + kaolin/sulfur + kaolin/sulfur/ azadirachtin	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus x7 + lime sulfur	54.4
22	ORG	kaolin/lime sulfur + kaolin/calcium carbonate	azadirachtin/rosemary oil + rosemary oil + azadirachtin + kaolin/azadirachtin + kaolin/ azadirachtin	38.8
25	ORG	kaolin/lime sulfur + kaolin/azadirachtin	kaolin/azadirachtin + calcium carbonate/azadirachtin + spinosad/azadirachtin/ codling moth granulosis virus + calcium carbonate/azadirachtin + azadirachtin/rosemary oil x4	46.5
28	ORG	lime sulfur + kaolin + azadirachtin	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus + spinosad + azadirachtin/codling moth granulosis virus x3	35.1

[1] Projected natural enemy impact was calculated for each spray used during the season in each site. Individual product ratings for western predatory mites, mite predators, coccinellids, lacewings and predatory true bugs were converted to numerical ratings from low (1), low to medium (2), medium (3), medium to high (4) and high (5) given in the Washington State University Crop Protection Guide (DuPont et al., 2020). An individual product's score is the average of the rating for each of the five natural enemy types. A site's score is the sum of the score for each spray used where higher scores equal higher natural enemy impact.
[2] sprays included petroleum oil.
[3] sprays included calcium chloride
[4] (xX) denotes the same spray used X times in a row.

Table Appendix 2
Pesticide Program and Natural Enemy Impact Scores 2018.[1]

Site	System	Pre-Bloom Sprays[2]	Post-Bloom Sprays[2,3]	Score
1	IPM	kaolin + kaolin/sulfur/ diflubenzuron + kaolin/calcium carbonate/ diflubenzuron	calcium carbonate/pyriproxyfen x2[4] + calcium carbonate/azadirachtin x3 + rosemary oil/ azadirachtin x2	45.1
3	IPM	calcium carbonate/novaluron/abamectin	calcium carbonate/novaluron/spirotetramat + calcium carbonate/azadirachtin + calcium carbonate/azadirachtin/spirodiclofen + calcium carbonate + azadirachtin/ spirodiclofen + buprofezin + bifenazate	41.2
5	IPM	kaolin + kaolin/sulfur/pyriproxyfen + kaolin/calcium carbonate/pyriproxyfen	calcium carbonate/azadirachtin x3 + calcium carbonate + calcium carbonate/azadirachtin x2 + rosemary oil/azadirachtin	41.1
6	IPM	lime sulfur + kaolin + kaolin/calcium carbonate/pyriproxyfen	calcium carbonate/azadirachtin/pyriproxyfen + calcium carbonate/azadirachtin x3 + rosemary oil/azadirachtin + rosemary oil/azadirachtin	33.4
9	IPM	kaolin + kaolin/sulfur/ pyriproxyfen + kaolin/calcium carbonate/ pyriproxyfen	calcium carbonate/azadirachtin x2 + calcium carbonate + calcium carbonate/azadirachtin x2 + bifenazate + rosemary oil/azadirachtin x2	43.5
12	IPM	kaolin + kaolin/lime sulfur + kaolin/calcium carbonate/pyriproxyfen	calcium carbonate/azadirachtin/pyriproxyfen + calcium carbonate/azadirachtin x2 + petroleum oil x3	36.1
15	IPM	kaolin/sulfur/azadirachtin + azadirachtin	azadirachtin + azadirachtin/codling moth granulosis virus + azadirachtin x4	27.7

(*continued on next page*)

Table Appendix 2 (*continued*)

Site	System	Pre-Bloom Sprays[2]	Post-Bloom Sprays[2,3]	Score
18	IPM	lime sulfur + kaolin + abamectin/azadirachtin	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus + azadirachtin + azadirachtin + spinetoram/ thiamethoxam + calcium carbonate/spirotetramat/ thiamethoxam + spinetoram/ spirodiclofen + acetamiprid/ fenpyroximate + spinetoram/acetamiprid/ cyflumetofen	70.2
2	CONV	kaolin + kaolin/malathion/ chlorpyrifos + kaolin/calcium carbonate/ acetamiprid/pyridaben/novaluron	calcium carbonate/thiamethoxam/abamectin/ novaluron + calcium carbonate/spirotetramat/novaluron + spinetoram/ bifenazate + thiamethoxam/abamectin + buprofezin/ spirodiclofen/spirotetramat + spinetoram/ acetamiprid/cyflumetofen	91.7
4	CONV	kaolin + calcium carbonate/chlorpyrifos/malathion + calcium carbonate/novaluron/abamectin	calcium carbonate/spirotetramat/novaluron + calcium carbonate/buprofezin/spirotetramat/ etoxazole + spinetoram/imidacloprid/hexythiazox/ spirodiclofen + spinetoram/ spirodiclofen + buprofezin + bifenazate	66.3
7	CONV	kaolin/calcium carbonate/acetamiprid/ pyridaben/novaluron	calcium carbonate/thiamethoxam/abamectin/ novaluron + calcium carbonate/novaluron/spirotetramat + spinetoram/ bifenazate + thiamethoxam/abamectin + buprofezin/ spirotetramat/spirodiclofen + spinetoram/ acetamiprid/cyflumetofen	38.1
11	CONV	kaolin/chlorpyrifos/malathion + novaluron/ lambda-cyhalothrin/abamectin + novaluron/ thiamethoxam/abamectin	novaluron/ spirotetramat + spinetoram + thiamethoxam/ fenpyroximate + spinetoram/ cyflumetofen + imidacloprid	84
14	CONV	kaolin + kaolin/malathion/ chlorpyrifos + kaolin/calcium carbonate/ acetamiprid/pyridaben/novaluron	calcium carbonate/thiamethoxam/abamectin/ novaluron + calcium carbonate/spirotetramat/novaluron + spinetoram/ bifenazate + thiamethoxam/abamectin + buprofezin/ spirodiclofen/spirotetramat + spinetoram/ acetamiprid/cyflumetofen	91.7
17	CONV	kaolin/sulfur + kaolin/novaluron/ acetamiprid	novaluron/spirotetramat + novaluron/spirotetramat/ spinetoram + thiamethoxam/fenpyroximate/ imidacloprid + acetamiprid/azadirachtin/ spirodiclofen + spinetoram/cyflumetofen/ imidacloprid	73.5
20	CONV	kaolin/sulfur/Cobalt Advanced/malathion + acetamiprid/ novaluron	calcium carbonate/spinetoram/novaluron + calcium carbonate/spirotetramat/novaluron + spinetoram/ thiamethoxam + calcium carbonate/spirotetramat/spirodiclofen + spinetoram/ imidacloprid/cyflumetofen	74.5
8	ORG	kaolin + lime sulfur + kaolin/sulfur + kaolin/*Bacillus thuringiensis* subsp. kurstaki	calcium carbonate/azadirachtin x2 + rosemary oil/ azadirachtin x2	73.8
10	ORG	kaolin/sulfur + kaolin/lime sulfur + kaolin/calcium carbonate + calcium carbonate/azadirachtin	spinosad/azadirachtin/codling moth granulosis virus x3 + azadirachtin/codling moth granulosis virus x4 + lime sulfur	47.1
13	ORG	kaolin/sulfur + kaolin/sulfur + kaolin/ calcium carbonate/azadirachtin	calcium carbonate/azadirachtin/*Isaria fumosorosea* apopka strain 97/pyrethrin + calcium carbonate/ azadirachtin/*Isaria fumosorosea* apopka strain 97 + spinosad/azadirachtin/codling moth granulosis virus/rosemary oil + azadirachtin/rosemary oil x2 + cinammon oil + lime sulfur	45.5
16	ORG	kaolin/sulfur + kaolin/sulfur/azadirachtin	azadirachtin + azadirachtin/codling moth granulosis virus + azadirachtin x2 + lime sulfur/cinammon oil	36.4
19	ORG	lime sulfur + kaolin + azadirachtin	azadirachtin/*Bacillus thuringiensis* subsp. kurstaki + azadirachtin/codling moth granulosis virus + cinammon oil x2 + lime sulfur	28.7

[1] Projected natural enemy impact was calculated for each spray used during the season in each site. Individual product ratings for western predatory mites, mite predators, coccinellids, lacewings and predatory true bugs were converted to numerical ratings from low (1), low to medium (2), medium (3), medium to high (4) and high (5) given in the Washington State University Crop Protection Guide (DuPont et al., 2020). An individual product's score is the average of the rating for each of the five natural enemy types. A site's score is the sum of the score for each spray used where higher scores equal higher natural enemy impact.

[2] Sprays included petroleum oil.

[3] Sprays included calcium chloride.

[4] (xX) denotes the same spray used X times in a row.

Table Appendix 3
Pesticide Program and Natural Enemy Impact Scores 2019.[1]

Site	System	Pre-Bloom Sprays[2]	Post-Bloom Sprays[2,3]	Score
1	IPM	kaolin + kaolin/sulfur/pyriproxyfen + kaolin/calcium carbonate/pyriproxyfen	kaolin/calcium carbonate/azadirachtin + calcium carbonate/azadirachtin + calcium carbonate/azadirachtin + azadirachtin x3[4]	33.8
5	IPM	kaolin + kaolin/lime sulfur	kaolin/calcium carbonate/pyriproxyfen + calcium carbonate/azadirachtin x2 + azadirachtin + petroleum oil x2 + chlorantraniliprole	26.1
6	IPM	kaolin/lime sulfur + kaolin/calcium carbonate/pyriproxyfen	calcium carbonate/azadirachtin x3 + azadirachtin + petroleum oil x2	24.4
12	IPM	kaolin + kaolin/lime sulfur + kaolin/calcium carbonate/pyriproxyfen	calcium carbonate/buprofezin/azadirachtin + calcium carbonate/pyriproxyfen/azadirachtin + calcium carbonate/azadirachtin + azadirachtin + petroleum oil x2	30.1
15	IPM	kaolin/sulfur + kaolin/sulfur/azadirachtin	azadirachtin x3	23.4
2	CONV	kaolin + kaolin/malathion/chlorpyrifos + kaolin/calcium carbonate/tolfenpyrad	calcium carbonate/thiamethoxam/tolfenpyrad/abamectin + calcium carbonate/novaluron/acetamiprid + spirotetramat/etoxazole + thiamethoxam/spirodiclofen/spirotetramat + spinetoram/ fenazaquin + spinetoram/imidacloprid/cyflumetofen	67.4
7	CONV	kaolin/malathion/chlorpyrifos + kaolin/calcium carbonate/tolfenpyrad	calcium carbonate/thiamethoxam/tolfenpyrad/abamectin + calcium carbonate/novaluron/acetamiprid + spirotetramat/etoxazole + spirotetramat/thiamethoxam/spirodiclofen + spinetoram/ fenazaquin + spinetoram/imidacloprid/cyflumetofen	63.7
11	CONV	kaolin + kaolin/malathion/tolfenpyrad + kaolin/calcium carbonate/acetamiprid	thiamethoxam/tolfenpyrad/abamectin + calcium carbonate/novaluron/acetamiprid + spinetoram/etoxazole + spinetoram/imidacloprid/spirodiclofen + spinetoram/ imidacloprid/cyflumetofen	67.3
14	CONV	kaolin + kaolin/malathion/chlorpyrifos + kaolin/calcium carbonate/tolfenpyrad	calcium carbonate/thiamethoxam/tolfenpyrad/abamectin + calcium carbonate/novaluron/acetamiprid + spirotetramat/etoxazole + spirotetramat/Actar/Spirodiclofen + spinetoram/ fenazaquin + spinetoram/imidacloprid/cyflumetofen	67.4
17	CONV	kaolin/sulfur/malathion/chlorpyrifos + kaolin/novaluron/acetamiprid	novaluron/acetamiprid/tolfenpyrad/abamectin + spirotetramat/tolfenpyrad/abamectin + calcium carbonate/thiamethoxam/cyflumetofen + spirodiclofen/fenazaquin + spinetoram/buprofezin/ cyflumetofen + acetamiprid/imidacloprid/spinetoram	74.2
18	CONV	kaolin/malathion/chlorpyrifos/lambda-cyhalothrin + novaluron/abamectin	calcium carbonate/tolfenpyrad/spirotetramat + calcium carbonate/tolfenpyrad/novaluron + spinetoram/spirotetramat/spirodiclofen + thiamethoxam/spirotetramat/ fenpyroximate + spinetoram/acetamiprid/bifenazate + acetamiprid/imidacloprid/cyflumetofen + petroleum oil	76.3
20	CONV	kaolin/malathion/chlorpyrifos/lambda-cyhalothrin + novaluron/abamectin	calcium carbonate/tolfenpyrad/spirotetramat + calcium carbonate/tolfenpyrad/novaluron + spinetoram/spirotetramat/spirodiclofen + thiamethoxam/spirotetramat/ fenpyroximate + spinetoram/acetamiprid/bifenazate + acetamiprid/imidacloprid/cyflumetofen + petroleum oil	74.3
8	ORG	kaolin/lime sulfur + kaolin/calcium carbonate/*Bacillus thuringiensis* subsp. kurstaki	calcium carbonate/azadirachtin x2 + codling moth granulosis virus/azadirachtin + azadirachtin + petroleum oil x2 + lime sulfur	29.4
10	ORG	kaolin/lime sulfur + kaolin/calcium carbonate/sulfur + kaolin/calcium carbonate/ azadirachtin	calcium carbonate/azadirachtin x3 + azadirachtin x3	34.1
13	ORG	kaolin/lime sulfur + kaolin/calcium carbonate/azadirachtin	calcium carbonate/*Isaria fumosorosea* apopka strain 97/azadirachtin + *Isaria fumosorosea* apopka strain 97 + spinosad/azadirachtin + calcium carbonate/azadirachtin/rosemary oil + diatomaceous earth/azadirachtin/rosemary oil + azadirachtin/rosemary oil + azadirachtin + azadirachtin/rosemary oil	27.8
16	ORG	kaolin/sulfur + kaolin/sulfur/azadirachtin	azadirachtin x3	23.4
19	ORG	kaolin + azadirachtin	calcium carbonate/*Bacillus thuringiensis* subsp. kurstaki/azadirachtin + cinnamon oil + azadirachtin + calcium carbonate/azadirachtin + azadirachtin/codling moth granulosis virus + spinosad/codling moth granulosis virus x2	23.5

[1] Projected natural enemy impact was calculated for each spray used during the season in each site. Individual product ratings for western predatory mites, mite predators, coccinellids, lacewings and predatory true bugs were converted to numerical ratings from low (1), low to medium (2), medium (3), medium to high (4) and high (5) given in the Washington State University Crop Protection Guide (DuPont et al., 2020). An individual product's score is the average of the rating for each of the five natural enemy types. A site's score is the sum of the score for each spray used where higher scores equal higher natural enemy impact.

[2] Sprays included petroleum oil.

[3] Sprays included calcium chloride.

[4] (xX) denotes the same spray used X times in a row.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2020.104390.

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